A Monte Carlo Approach to Measuring Trajectory Performance Subject to Missed Thrust

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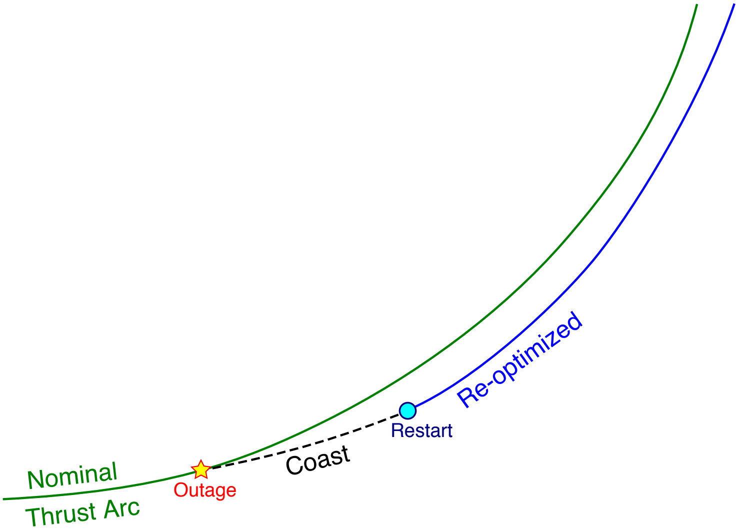
January 9, 2018

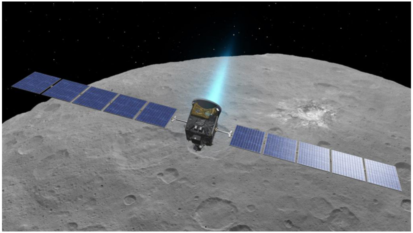
Missed Thrust Problem



It happened to Dawn!

September 11, 2014

- Dawn entered safe mode on approach to Ceres.
- Thrust stopped at the most critical time.
- 4-day outage led to 26-day delay in arrival.



Planning for Missed Thrust

Estimate Margins Required

- How much extra propellant should be budgeted for missed thrust?
- How much extra time should we put in our schedule?
- Simulate missed thrust events on the reference trajectory.

Design Robust Trajectories

- Develop new optimization methods for low-thrust trajectories that account for missed thrust.
- Not focus of this work.

Comparison of Missed Thrust Methods

Deterministic Method

- Repeatedly simulate single thrust outage at regular intervals.
- Quickly find sensitive points in trajectory.
- Difficult to extend to multiple outages
- Requires potentially arbitrary assumptions.

Probabilistic Method

- Run Monte Carlo simulation of many different outage scenarios.
- Inherently a multi-outage method.
- Computationally trickier—must make more decisions about outage recovery.
- Enabled by creation of safe mode database.

What are the odds of a safe mode?

We need a way of generating safe mode event scenarios that is consistent with reality.

Safe Mode Database

- Collect as much information as possible from past planetary missions about safe mode events: when did they happen? And how long did they last?
- Almost 200 (and counting) individual safe mode events captured in database.
- Joint Effort between JPL, Goddard, Ames, and APL.

Weibull Fit

From Event Database, Fit Two Weibull Distributions

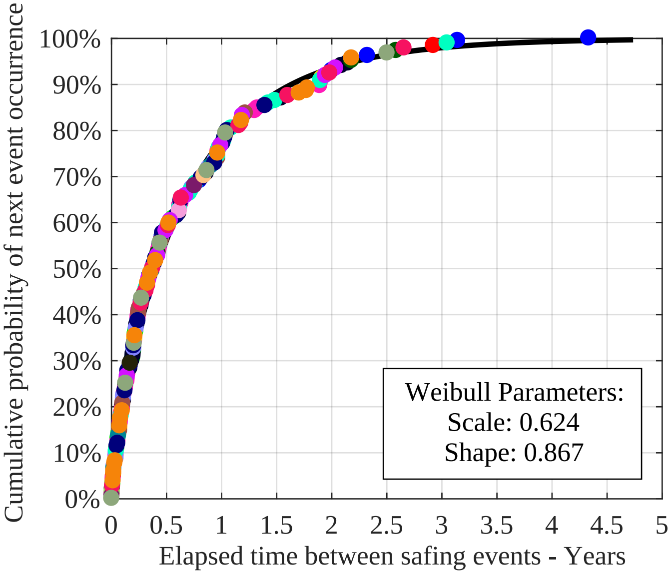
One for time between events, one for event duration.

Weibull probability density function:

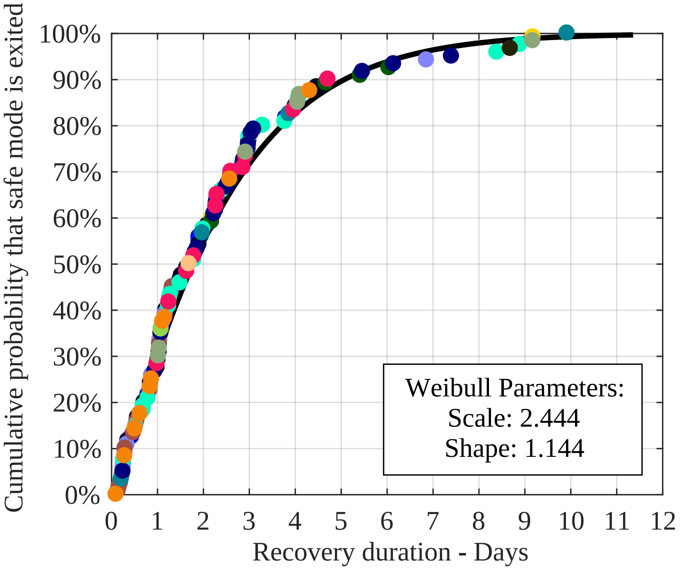
$$f(x;\lambda,k) = \begin{cases} \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k} & x \geq 0, \\ 0 & x < 0. \end{cases} \tag{1}$$

$\lambda =$ scale parameter, $k =$ shape parameter.

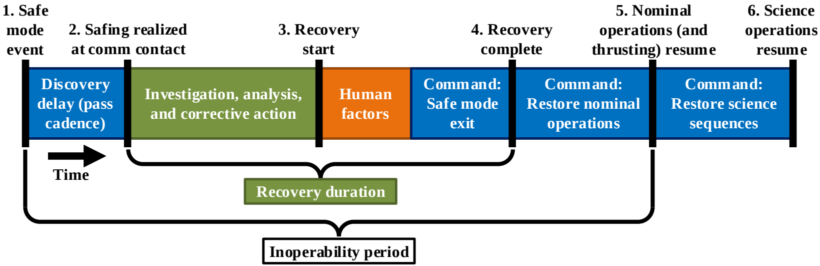
Time Between Events



Event Duration



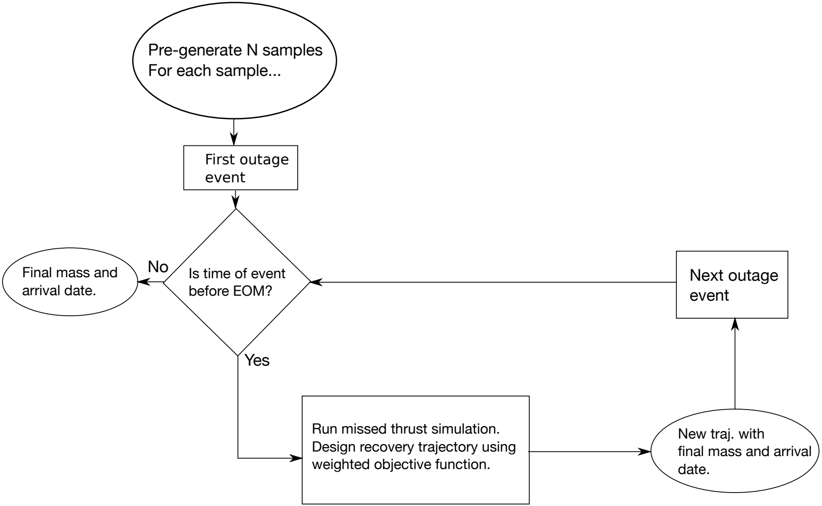
Event Duration



Example Sample

Event	Mission Day	Duration, d
1	36	4
2	90	3.2
3	310	2.8
4	560	7.2
...	...	...

Monte Carlo Missed Thrust Procedure



Performance Metrics

When Recovering from Missed Thrust

- Design new trajectory that reaches target while minimizing

$$J = -m_f + \eta T$$

- η is a user-selected weighting.

Collect Statistics for Each Run

- For each sample, track how late ($\bar{l}$) the spacecraft arrived and how much extra propellant ($\bar{m}$) it required to get there.

Re-run for different conditions

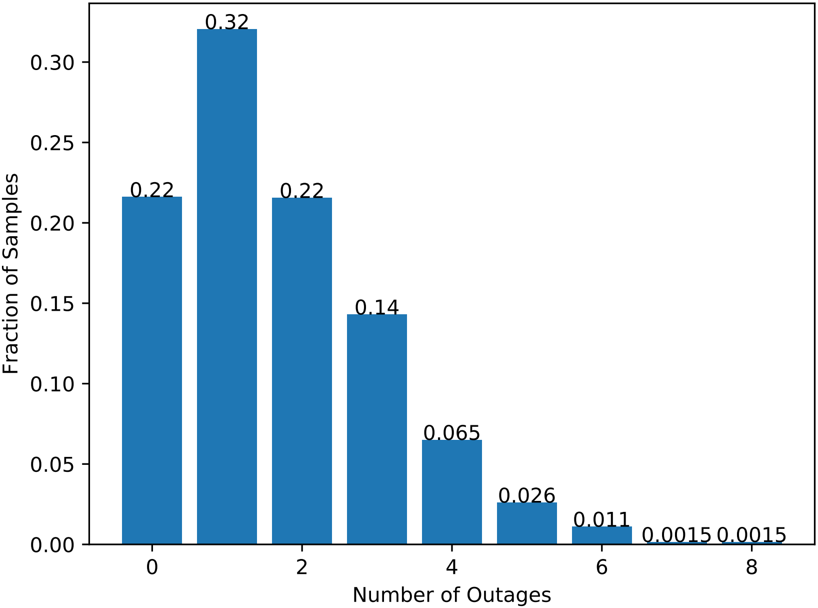
- η, DSN schedule, safe mode assumptions.

Example Trajectories

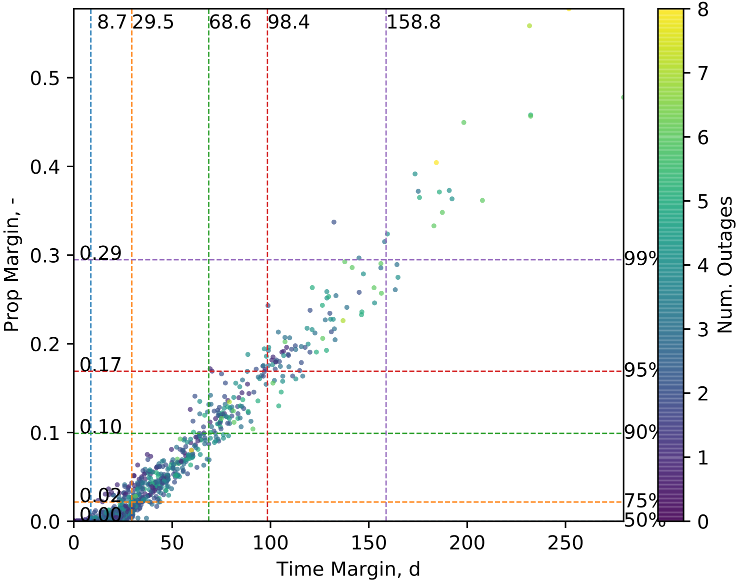
Table: Example Trajectory Characteristics

Prop. System	P_0, kW	m_0, kg	m_p, kg	TOF, days	C_3, km^2/s^2
NEXT×2	24.5	3565	261	405	13.2
HERMeS×1	30.5	4904	624	410	5.76

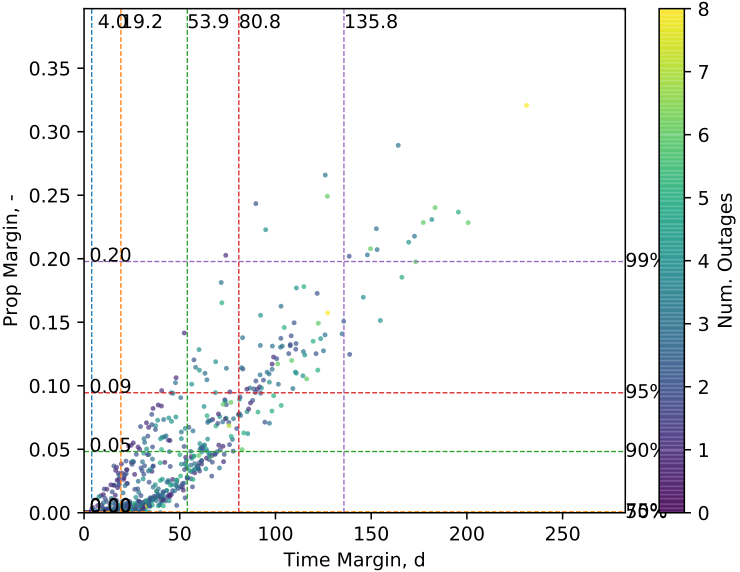
Distribution of Outages—NEXT



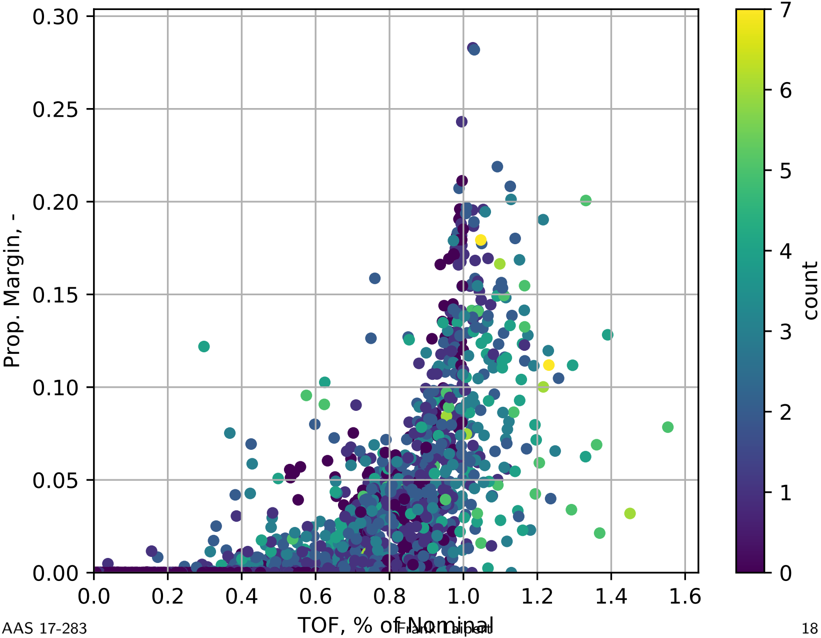
Scatter Plot—NEXT



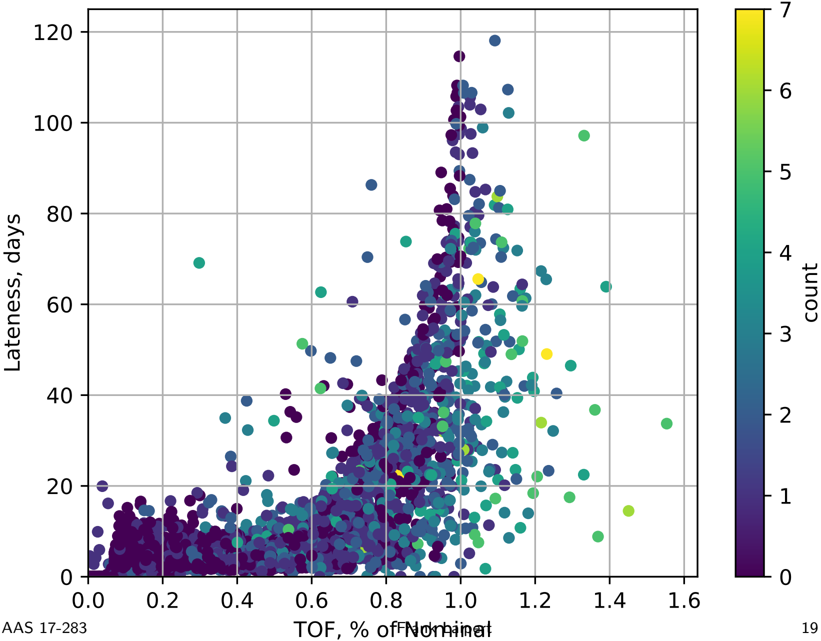
Scatter Plot—HERMeS



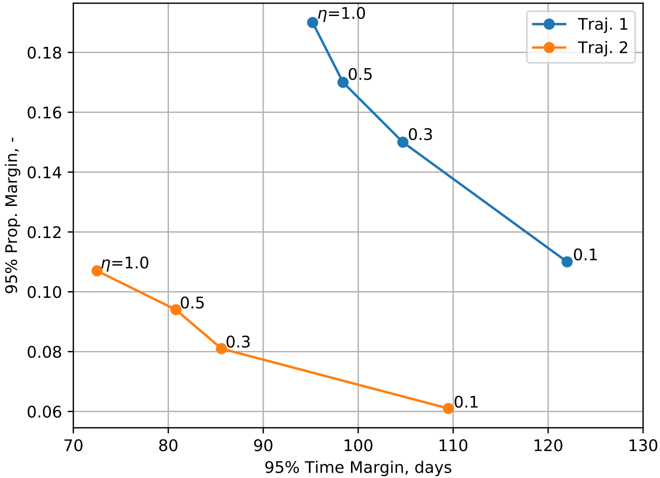
Individual Outage Propellant—NEXT



Individual Lateness Contributions—NEXT



Weighting Plot



Bad samples: What Sequences Cost the Most?

Table: $\bar{m}_{95}$ sample for Trajectory 2 with $\eta = 0.5$

N	Evt. Time, %TOF	Duration, d	$\bar{m}$	$\bar{I}$
1	57.6	4.8	0.000	2.7
2	87.1	1.9	0.014	35.7
3	91.0	1.2	0.057	10.8
4	99.5	2.4	0.024	19.4
Total	-	10.3	0.095	68.6

Future Work

Visualization

- What additional insight can we gain from advanced visualization techniques?

Outage Recovery

- Given a thrust outage a particular time, what is the best way to spend margin?
- Simulate the decision making process at the time of a missed thrust.

Conclusions

We have developed a probabilistic missed thrust analysis method that:

1. Simulates realistic outage sequences.
2. Leverages the results of a new historical study of safe mode events.
3. Enables setting statistical requirements on SEP missions regarding missed thrust.